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A simulation based development of Process Signatures for manufacturing processes with thermal loads

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Abstract

The newly developed concept of Process Signatures enables the comparison of surface integrity achieved by seemingly different manufacturing processes. This paper suggests Process Signatures for grinding and induction heating. Based on finite element simulations of both processes the relevant internal material loads are identified and are correlated with the simulated residual stress state. To provide a comparable simulation approach the moving heat source theory is applied and combined with energetic quantities. The investigations show that grinding and induction heating are similar for certain parameter regimes regarding the generated residual stress state of the workpiece surface layer.

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Keywords: Residual Stress, Grinding, Induction-heating, Process Signature

1. Introduction

The importance of manufacturing processes on the functional performance of components is generally known [1,2,3]. This is especially true for finishing processes such as grinding or hard turning which affect the functional performance by changing the workpiece surface layer properties, e.g. residual stresses, microstructure, and hardness. However, even under laboratory conditions a controlled generation of surface layer properties is not state of the art in machining [2].

It is assumed that this knowledge gap is the result of a process-oriented view that has been prevailing in the scientific analyses in which predominantly the resulting workpiece material modifications are correlated with the machining parameters and/or process quantities [4,5,6,7]. The reason is that internal material loads, i.e. stresses, strains, strain gradients, temperatures, and temperature gradients, which actually lead to the observable modifications are hard to determine or even not known at all. As a consequence the validity of the findings is very limited.

A material-oriented view which focusses on the mechanisms leading to workpiece material modifications by manufacturing processes, as the newly introduced concept of Process Signatures [8] intends, should resolve this lack of knowledge. In the frame of Process Signatures, the material modifications are correlated with the internal material loads that are assumed to cause the modifications by activating mechanisms such as plasticity (yielding) and/or phase transformations.

The Collaborative Research Center (CRC) 136 - Process Signatures aims at developing these correlations for different manufacturing processes to prove the validity of the concept. Moreover, the correlations between internal material loads and process quantities (e.g. in the case of grinding: process power, process forces, and machining parameters) will be developed to be able to utilize Process Signatures for a reproducible and defined generation of surface layer properties.

2. Objectives and Procedure

The present work aims at an exemplary simulation-based development of correlations between material modifications

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and internal material loads (Process Signature) and between internal material loads and process quantities. In order to reduce the complexity of the analyses, only yielding in the workpiece surface layer caused by thermal loads are taken into account. This can approximately be realized by shallow cut grinding and induction heating in certain parameter regimes where austenitization of the workpiece material not occurs.

Both processes were modelled as a moving surface heat source and a moving volume heat source, respectively (Fig. 1). The mechanical material load in grinding was neglected.

Temperature increases and temperature gradients can be viewed as the relevant internal material loads. This is evident because the temperature governs the thermal and mechanical material behavior, and temperature gradients $d\theta/dx$ are the origin of plastic strains. However, the results will show that for an appropriate description of the material loads other parameters also have to be taken into account.

In the present work material modifications were characterized by the surface residual stresses and the zero crossing of the residual stresses below the workpiece surface.

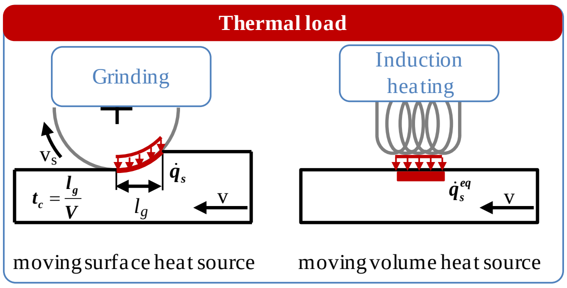

Fig. 1. Basic models of external thermal loads due to grinding and induction heating.

Nomenclature

a	thermal diffusivity [mm²/s]
b	exponent for calculating $\dot{q}_{Vol}$ [1/mm]
e	thermal effusivity [J/(K mm^2 s^{0,5}]
l_g	contact length [mm]
P_C	specific grinding power [W/mm²]
Pe	Peclet number $l_g \cdot V/(4 \cdot a)$ [-]
$\dot{q}$	heat flux ($\dot{q}_S$ or $\dot{q}_S^{eq}$)[W/mm²]
$\dot{q}_S$	heat flux through the workpiece surface [W/mm²]
$\dot{q}_S^{eq}$	equivalent heat flux (calculated with $\dot{q}_{Vol}$) [W/mm²]
$\dot{q}_0$	factor for calculating $\dot{q}_{Vol}$ [W/mm³]
$\dot{q}_{Vol}$	heat per volume unit [W/mm³]
$\sigma\|$	residual stress parallel to workpiece velocity [MPa]
θ	temperature [°C]
θ_{max}	maximum temperature [°C]
$d\theta/dx$	temperature gradient normal to surface [K/mm]
t_c	contact time [s]
V	workpiece velocity [mm/s]
x	distance from the heated surface [mm]

3. Methods

3.1. Preliminary considerations

After Malkin [9] maximum temperatures for a moving surface heat source occur at the surface and can be approximated by the following analytical function:

$$\Theta_{max} = 1.13 \cdot \frac{1}{e} \cdot \dot{q}_S \cdot \sqrt{t_c} = 1.13 \cdot \frac{1}{e} \cdot \dot{q}_S \cdot \sqrt{\frac{l_g}{V}} \tag{1}$$

in which the factor 1.13 results from assuming an infinite Peclet number. In a double-logarithmic plot proposed by Heinzel et al. [10] constant $\dot{q}_S \cdot \sqrt{t_c}$ values describe straight lines of constant maximal temperatures at the surface (Fig. 2). For higher temperatures than 750 °C a martensitic phase transformation might occur as intended in grind-hardening (grey framed area).

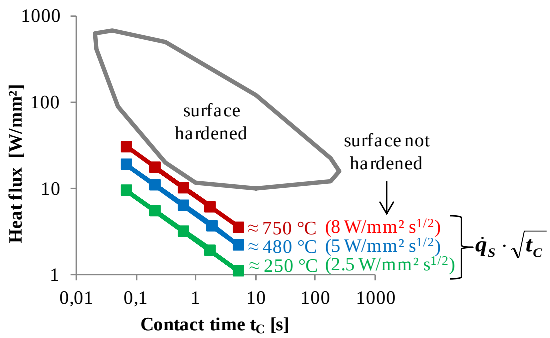

Fig. 2. Process window for grind-hardening [10].

In case of a volume heat source an equivalent surface heat flux $\dot{q}_S^{eq}$ has to be defined:

$$\dot{q}_s^{eq} = \int_0^\infty \dot{q}_{Vol} dx = q_0 \cdot \int_0^\infty e^{-bx} dx\,. \tag{2}$$

$\dot{q}_{Vol}$ represents the heat per volume unit depending on the distance x to the heated surface. The penetration depth of $\dot{q}_{Vol}$ is defined by *b* which equals 3.56·1/mm. This value describes approximately an induction heating with 12 kHz [11]. In the following $\dot{q}_S$ and $\dot{q}_S^{eq}$ will be used as equivalent values and will be denoted with $\dot{q}$.

3.2. Simulation parameters

According to the preliminary considerations in section 3.1 the process quantities in the simulation study were chosen in such a way that maximal temperatures at the surface of about 250, 450, and 750 °C were achieved: l_g = 4 – 20 mm, V = 4 - 60 mm/s, $\dot{q}$: = 1 – 39 W/mm².

The 3D simulations with the finite element code SYSWELD were carried out under the following conditions:

- Geometry: length 50 mm, width 30 mm, height 18 mm
- Temperature dependent material parameters for 42CrMo4 (Ferrite and Pearlite) [13]. Stress strain curves for temperatures up to 750°C were measured with a strain rate of approximately $3 \cdot 10^{-3}$ s^{-1}

- A constant heat transfer coefficient of 100 W/(m²K) (cooling in still air) was assumed [12].

4. Results

4.1. Correlation of process quantities and temperatures

As assumed in section 2 the appropriate internal material loads should closely be connected to the changes of temperature and temperature gradients during the considered heating process. In figure 3 six examples of temperature distributions with the same Peclet number are shown. In all cases the term $\dot{q}_S \cdot \sqrt{t_C}$ equals 8 $W\sqrt{s}/mm^2$. Under these conditions the temperature increases at the surface to approximately 600 to 750 °C. In all cases the maximal temperature occurs at the surface. However, maximal surface temperatures for volume heating are considerably lower than for heating through the surface.

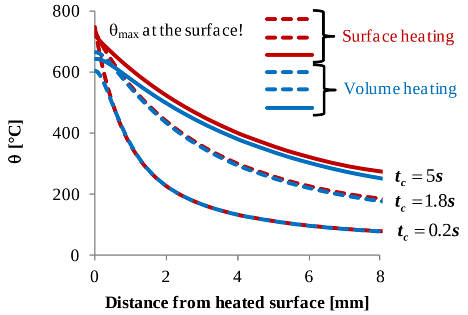

Fig. 3. Temperature distribution at the moment of maximal temperature at the surface for different contact times t_C (5, 1.8, and 0.2 s). Pe = 3.17

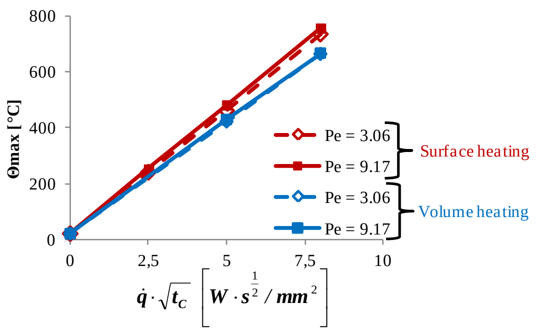

Fig. 4. Linear dependency of θ_{max} on $\dot{q}_S\sqrt{t_C}$ for surface and volume heating.

Due to the diffusive nature of heat propagation in a solid, the temperature evolution normal to the surface depends strongly on the contact time t_C. A closer investigation of all simulated cases reveals, as expected, a $\sqrt{t_C}$ - dependency of the temperature penetration depth.

It is noteworthy that although the finite element model considerably differs from the analytical model of a moving surface heat source (finite geometry, temperature dependent material parameters, non adiabatic system) the proportionality of θ_{max} and $\dot{q}_S\sqrt{t_C}$ according to Malkin's approximation (eq. (1)) still remains valid, even for a moving volume heat source. In the investigated range the Peclet number does not significantly affect the linearity and the maximum temperature at the surface (Fig. 4).

4.2. Correlation of process quantities and temperature gradients

In Figure 5 exemplary temperature gradients for surface and volume heating are plotted over the distance to the surface. With the exception of the heating method all process quantities are equal. Figure 5 points out the main differences between both heating methods. Firstly, the maximal temperature gradient for surface heating occurs at the surface whereas for volume heating it occurs below the surface. Secondly, the magnitude of the gradient is significantly lower in the case of volume heating. At a depth of approximately 1 mm the temperature gradients become nearly equal.

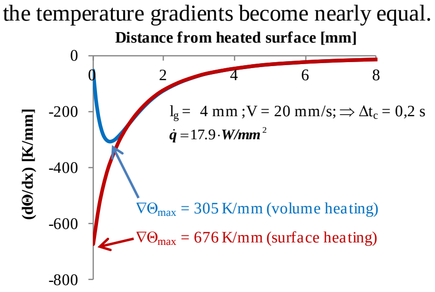

Fig. 5. Examplary depth profiles of temperature gradients for surface and volume heating at the moment of maximal temperature at the surface.

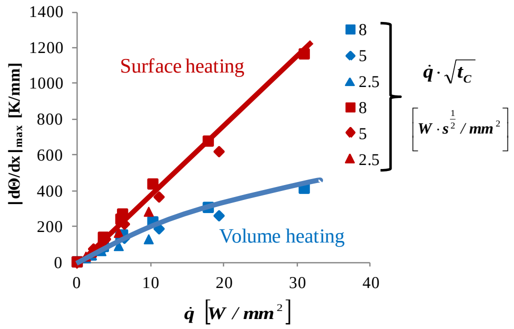

Fig. 6. Absolute value of the maximal temperature gradients at the moment of maximal temperature at the surface.

Figure 6 summarizes all calculated maximal temperature gradients plotted over $\dot{q}$ ($\dot{q}_S$ or $\dot{q}_S^{eq}$, respectively). For surface heating the maximal temperature gradients increase nearly linear with $\dot{q}$ whereas presumably a non-linear dependence for a moving volume heat source exists.

4.3. Correlation of internal material loads and material modifications (Process Signatures)

Figure 7 shows the dependency of the residual surface stresses in feed direction on the maximal temperature gradients. The results strongly suggest that in the investigated range the maximal temperature gradient is a sufficient characteristic measure of the internal material load with respect to the residual surface stress. The type of heating has no significant influence. The residual stress perpendicular to the feed direction is not plotted here because it shows a similar behavior.

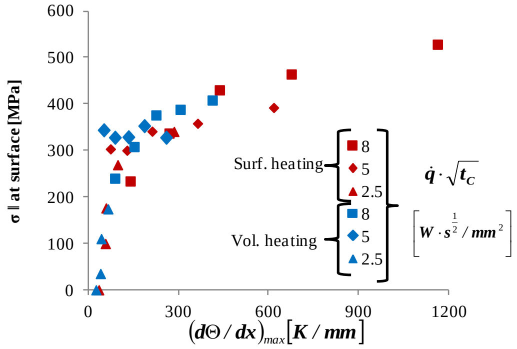

Fig. 7. Residual surface stresses parallel to the feed direction over the maximal temperature gradient for surface and volume heating.

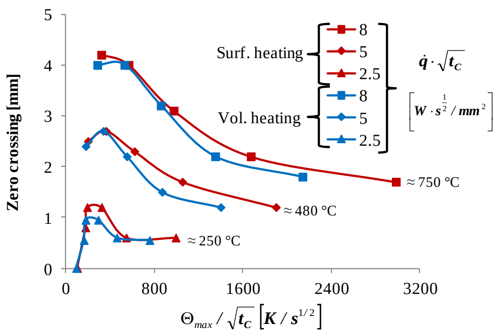

Fig. 8. Zero crossing plotted over $\theta_{max}/\sqrt{t_C}$ for surface and volume heating at different maximal temperatures.

In order to determine the depth of the sign change of the residual stress below the surface (zero crossing) as another characteristic of the material modification, it is necessary to investigate the main factors which govern the temperature penetration depth and the heating rate. The $\sqrt{t_C}$-dependency of the temperature distribution has already been mentioned in section 4.1. However, two further factors have to be taken into account: the maximal temperature at the surface (Fig. 4) and the mean rate at which the temperature increases at the surface: θ_{max}/t_c. Figure 8 presents the position of the zero crossing over the product of $\sqrt{t_C}$ (temperature penetration depth) and θ_{max}/t_c (mean temperature rate). Additionally, the zero crossing depends on the maximal temperature θ_{max}.

5. Conclusions and Outlook

For the first time Process Signatures have been developed in a theoretical study. In the presented examples of moving surface and volume heat sources the temperature gradient has been identified as an appropriate characteristic that governs the generation of residual surface stresses caused by yielding.

For the calculation of the zero crossing things are more complicated. In that case the product $\sqrt{t_C} \cdot \theta_{max}/t_c$ is an appropriate internal material load. The observation that the type of heating has a slight influence on the results indicates that the Process Signatures of both processes are comparable but do not overlap completely. However, the difference for the analyzed correlations is quite small.

The presented analyses of correlations between internal material loads with process quantities and material modifications provide a possibility to engineer the workpiece surface layer properties in a knowledge-based way. If a specific residual stress at the surface and a specific zero crossing is sought, the necessary internal material loads and with the availability of process models the necessary process parameters are determinable.

The example illustrates that setting up Process Signatures as a new way of describing manufacturing processes is feasible. In future work the simulation based approach presented here will be verified with experimental data. Moreover, a broader range of material loads, e.g. thermo-mechanical load and other material modification mechanisms such as phase transformations will be taken into account.

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